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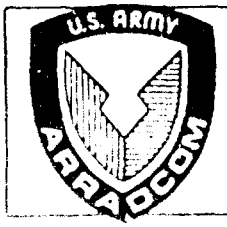
# THE BURNING BEHAVIOR OF TNT IN THE CLOSED BOMB

RODOLF W. VELICKY

MARCH 1983

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The work shows that the physical structure of TNT breaks up during burning. Combustion proceeds on fragments with a new surface to volume ratio. The size, shape, and number of fragments is determined by the crystal pattern permitted to develop by the casting procedure. The intrinsic burning rate of TNT is very slow in relation to the rate of structural dissociation. Wax, the desensitizing agent used with TNT in the mixture Comp B, does not interact with TNT to modify its burning behavior.

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## INTRODUCTION

TNT burns in an anomalous manner. Contrary to the burning behavior of gun propellants, cast and pressed samples react at a rate that is essentially independent of the initial geometrical configuration, i.e., surface area to volume ratio. Since TNT is used in large caliber explosive filled projectiles, and is a major constituent of the explosive Comp B, it is important to understand its idiosyncracies in order to unravel the anomalous burning characteristics reported for it and for Comp B (ref 1).

This work identifies the major factors controlling TNT's burning mechanism and provides a foundation for subsequent evaluation of its role in the combustion process of Comp B. It is intended as a broad overview, with the conclusions providing guidelines for further study.

## EXPERIMENTAL

Closed bomb data, in relation to gun propellant linear burning rate regression theory, provided the foundation for this work. The theory states that the burning rate is an intrinsic property of the composition. Utilizing suitable techniques, the burning rate equation can readily be calculated from closed bomb pressure versus time data. The method is routinely used to evaluate gun propellant formulations (ref 2).

If a sample burns only on its exterior surface after the entire surface area is simultaneously ignited, essentially the same constants are developed for the equation:

$$r = ap^n$$

for any known geometrical configuration. When the same constants are not developed, for samples with different surface area to volume ratios (So/Vo), it means that the samples are burning on a surface area that is different than that predicted by linear regression of the initial surface area. This can happen through the fragmentation of the physical structure, penetration of burning into a porous body, or distortion of the surface area by massive melting.

When experiments are designed with specific goals, insight into unusual burning behavior can be gained from analysis of the quickness curve (dp/dt vs pressure). These curves are particularly useful when used to compare the effect of controlled differences, i.e., surface area, density, crystal size composition, etc. Based on the design of the experiment, valid inferences on the cause and effect relationship can be made.

### Instrumentation

Details of the method are described in reference 1. Briefly stated, a heavy-walled vessel was provided with a closure, insulated firing electrode, and an exhaust valve. The pressure-versus-time data of a burning sample was sensed

with a piezo pressure transducer, collected with a Nicolett Explorer III digital oscilloscope, and permanently stored on magnetic discs. The data was then easily retrieved and processed with a Hewlett-Packard HP-85 desk top computer for various listings and plots.

## Procedure

Some results on cast and pressed TNT are reported in reference 1. These results and data on crushed TNT, flake TNT, and TNT cast with wax will be discussed in more detail. This group of experiments was performed in a 201 $cm^3$ (12.27 $in^3$) bomb on single grain cylindrical samples. Questions stimulated by these experiments were addressed by a second group of experiments in a 252 $cm^3$ (15.38 $in^3$) vessel on samples burned under partial confinement in steel cups.

Precise cylindrical geometries were machined for cast TNT, pressed TNT, and TNT with wax. They were machined to provide two significantly different surface area to volume ratios for each sample. They were 2.54 cm (1.000 in.) diameter cylinders. One was solid and the other, a single perforated grain, contained a 0.953 cm (3/8 in.) diameter hole in the center. The lengths were adjusted to provide a constant mass, and were approximately 5 cm (2 in.) long. Crushed and flake forms of TNT were also tested. Each test was provided with massive thermal ignition by 5 grams of class 7 black powder. This was done to insure simultaneous ignition of the entire surface area.

# RESULTS AND DISCUSSION

## Test for Surface Area Burning, Cast TNT

The purpose of this experiment was to determine whether or not cast TNT burns by regression that is normal to its exterior surface. If this occurred, the two different geometries, described in Experimental, would generate the same constants for the linear burning rate equation. The quickness curve (dp/dt vs pressure), which provided the foundation for the calculation, must vary with respect to the surface area as a function of the volume fraction burned in order for the calculations to apply. The quickness curves for each of the two geometries were identical (fig. 1) (table 1). The solid and 3/8 single perforated grains are represented, respectively, by dotted and solid lines.

A common burning rate equation could not be generated for the two geometries. This could only mean that the physical structure has changed and provided a new surface area that is not represented by the original geometry. This can only be explained by the creation of a new common surface area from the initial geometries. This can happen through the complete breakup of TNT's physical structure or through its deformation, as might occur through massive melting.

## Test for Surface Area Burning, Pressed TNT

Essentially, the same conclusions were drawn for pressed TNT as were drawn for cast TNT. The quickness curves for pressed TNT also show that a surface area alteration had taken place which produces similar burning from the two different geometries (fig. 2) (table 2).

Even though the density of the pressed TNT (1.59 $g/cm^3$) was slightly higher than the cast TNT (1.56 $g/cm^3$), it should be noted that it burns at a considerably slower rate than the cast TNT. This is an important observation and will be addressed by later experiments.

## Crushed and Flake TNT Compared with the Solid Grain

Equal masses of crushed and flake TNT were also burned. Material from the same TNT casting was physically crushed into an aggregate of fine powder and small chunks. The flake TNT was thin oblong material [approximately 0.953 cm x 0.079 cm (3/8 in. x 1/32 in.)] from which all the castings were made. Although their surface to volume ratios (So/Vo) were not determined. This ratio was two to three orders of magnitude greater than each machined grain. The ratio for the crushed form was estimated to be at least ten times greater than the flake form. Figure 3, table 3, compares the quickness of crushed and flake TNT with the cast solid cylindrical grain.

All things being equal (mass, composition, etc.), the quickness (dp/dt) is directly related to the surface area burning. This comparison shows that the crushed TNT, with a surface area on the order of a thousand times greater than its solid cylindrical form burns only 20% faster. This strongly reinforces the conclusion drawn earlier that TNT is changing its surface area through fracturing and/or melting its physical structure.

Based on the tests performed thus far and the So/Vo relationship of the crushed and flake forms, one would expect the flake TNT to burn equal to or slower than the crushed TNT. In spite of having a smaller initial surface area, the flake TNT, surprisingly, burned faster than its recast crushed version. This suggested that the burning characteristics of TNT had been changed by the melting and recasting process. This point will be addressed by later experiments.

## TNT with 2.5% Wax Additive Compared with Cast TNT

The 1% wax additive in Comp B significantly effected its burning behavior (ref 1). In order to determine if this effect was due to an interaction of the wax with TNT, an attempt was made to mix an equivalent quantity (2.5%) directly into the TNT. This was very difficult. In the melt, the wax appeared to be unmixable with the TNT. However, the mixture was homogenized and quickly cooled to lock the wax within the TNT casting. The waxy feel of the machined casting and the change in physical appearance indicated that a significant quantity of wax was locked in the casting.

Figure 4 compares the solid cylinder geometry of cast TNT with the solid cylinder geometry of TNT with added wax. There was no significant difference in

the results. TNT burned essentially the same with or without wax. The question of the role of wax in the combustion of Comp B will be addressed in a future report.

In table 4, the two geometrical forms of TNT are compared. The same independence of geometry behavior, previously noted for cast and pressed TNT, is observed for TNT with wax.

## Test for Melting or Fragmentation of TNT

The previous experiments show that the physical structure of TNT changes independently of the original configuration during burning. This experiment was designed to indicate whether this change is due to melting or fragmentation (breakup) of the physical structure. Equal masses of TNT were cast in open cylindrical steel cups that should permit burning on only one surface. The surface provided by one set of cups was 3.81 cm (1.5 in.) in diameter and the other was 1.91 cm (0.75 in.) in diameter (fig. 5). These samples were ignited with 3 grams of class 7 black powder within a "Parr" high pressure bomb.

If TNT melts during burning, it is assumed that it will remain in the cup and the burning will take place on the restricted surface area defined by the diameter of the cup. The rate of burning would be related to the ratios of the surface areas. The TNT in the large diameter cup would burn faster than that in the small diameter cup and it should be possible to calculate TNT's linear burning rate.

If TNT was burning through a fragmentation process, it was expected that the quickness curves would be, as previously observed, the same for the two geometries. The results are shown in figure 6 and table 5.

The reverse of what should happen for a melting mechanism occurred. The sample with the smaller surface area actually burned faster. These results eliminate the melting mechanism as a possible explanation for the observations. It is therefore inferred that TNT burns predominantly by the deconsolidation of its physical structure. Fragments are created at an extremely rapid rate in relation to the burning time of the fragments. This is indicated because the quickness curves for the two machined geometries (cast and pressed) are virtually identical. If the fragments were created at a rate that was within their total burning time, there would be a meaningful difference between the two curves.

The quickness curves for the TNT burned in the two cup sizes does not conform to that expected for the fragmentation mechanism. The two quickness curves were expected to be identical; instead, samples with the small surface area burned faster. Fortunately before the burning, it had been noticed that this casting, because of a slow rate of cooling, had permitted the growth of a long, needle-like, crystal pattern. The larger diameter casting had been fast-cooled. Its crystal pattern was not visually structured.

Effect of Crystal Structure On The Burning of Cast TNT

Through serendipity it was indicated that TNT's crystal formation procedure had a significant effect on its burning behavior.' In order to test this observation castings were made in the large diameter cup. One group was permitted to cool rapidly, while the other was allowed to crystalize slowly over a period of several hours. The quickly cooled casting had again, a visually undefined crystal structure, whereas the slowly cooled sample had a radially oriented pattern of long thin crystals. The result of the burnings are shown in figure 7 and table 6. The TNT with the long, thin, needle-like, crystal structure burned much faster than its unstructured counterpart.

The Effect of Density on the Burning of Pressed TNT

Although the densities were not comparable, it has been observed in a previous experiment that pressed TNT burned significantly slower than cast TNT. In order to clarify the meaning of this observation, a spectrum of densities were pressed into the larger diameter metal cups. The quickness of these samples is related to the density (fig. 8), (table 7). It is ranked in inverse order of the pressed density; it increased as density decreased. A good correlation is shown between the maximum dp/dt and the density (fig. 9).

That density can increase with loading pressure, means that there are voids (porosity) in the material that became smaller with respect to the applied load. The fact that TNT could be pressed to higher densities, than usually occur in good castings, indicates that collapsible fissures are present in TNT castings. It is quite possible that as the density of TNT approaches its maximum theoretical density (TMD), the intrinsic burning rate of the composition would become measurable. This would be an interesting area for future study.

## CONCLUSIONS

1. The physical structure of TNT breaks up during the burning process. Fragments are rapidly created with a new, unknown, surface-to-volume ratio. The rate at which the structure dissociates is much faster than the intrinsic burning rate of the released fragment. The reactions combine the rate at which the physical structure dissociated, the surface-to-volume ratio of newly created fragment and the intrinsic burning rate of the composition.

2. The size, shape, and number of fragments is determined by the crystal pattern permitted to develop by the casting procedure.

3. Porosity was the major factor controlling the burning process in pressed TNT. Collapsible fissures (voids) that occurred naturally could exist in cast TNT. This was indicated by the fact that TNT could be easily pressed to higher densities than normally obtained in casting.

4. Porosity alone did not appear to provide a sufficient reason for the dissociation of the physical structure of TNT at the observed rapid rate. However, the existence of crystal patterns implies that there are boundary layers between neighboring crystals. These are areas of weakness, which could provide cleavage paths for dissociation of the structure. The inferred, built-in porosity might be associated with this boundary layer.

5. Wax did not interact with TNT to modify its burning characteristics.

## RECOMMENDATIONS

There are several parameters associated with the deconsolidating burning mechanism that are combined in the quickness measurement. They are the rate of structure dissociation, the average surface area of the dissociating fragment, and the intrinsic burning rate of the composition. Separated and measured, this data would provide a basis for understanding the deflagration side of the deflagration to detonation (DDT) mechanism.

Well-designed experiments utilizing the closed bomb could help separate these unknowns. Researchers should be encouraged and supported to use the close bomb in the investigation of explosive burning. It is an extremely versatile tool that is not used in proportion to its value.

## REFERENCES


1. R.W. Velicky and J. Hershkowitz, "Anomalous Burning Rate Charteristics of Composition B and TNT", Seventh Symposium (International) on Detonation, 1981.

2. A. Pallingston and M. Weinstein, "Method of Calculation of Interior Ballistic Properties of Propellants from Closed Bomb Data", Picatinny Arsenal Technical Report 2005, Picatinny Arsenal, Dover, NJ, June 1954.

Table 1. Surface burning test for cast TNT

| Pressure (MPa) | Quickness (MPa/ms) | | |
|---|---|---|---|
| | #1 | #2 | #3 |
| | Solid Cylinder | | |
| 30 | 5.57 | 5.59 | 5.56 |
| 40 | 7.80 | 7.83 | 9.31 |
| 50 | 10.82 | 10.05 | 10.51 |
| 60 | 14.64 | 13.14 | 14.31 |
| 70 | 17.32 | 16.65 | 17.07 |
| 80 | 19.36 | 17.82 | 18.51 |
| 90 | 20.63 | 19.59 | 20.49 |
| 100 | 22.99 | 21.99 | 22.69 |
| 110 | 24.32 | 23.25 | 24.32 |
| 120 | 26.14 | 25.39 | 26.53 |
| | 3/8 ID Single Perforated | | |
| 30 | 5.14 | 4.95 | 4.4 |
| 40 | 6.03 | 6.51 | 5.36 |
| 50 | 9.34 | 8.35 | 8.76 |
| 60 | 12.07 | 11.73 | 11.72 |
| 70 | 15.16 | 15.19 | 14.99 |
| 80 | 17.78 | 16.90 | 18.02 |
| 90 | 19.71 | 19.07 | 19.11 |
| 100 | 21.49 | 21.33 | 21.49 |
| 110 | 22.47 | 23.30 | 23.24 |
| 120 | 24.47 | 24.89 | 24.67 |

Table 2. Surface burning test for pressed TNT

| Pressure (MPa) | Quickness (MPa/ms) | | |
|---|---|---|---|
| | #1 | #2 | #3 |
| | Solid Cylinder Geometry | | |
| | (Density = 1.59 g/cc) | | |
| 30 | 1.56 | 1.43 | 2.30 |
| 40 | 3.65 | 4.09 | 3.21 |
| 50 | 5.06 | 5.66 | 5.76 |
| 60 | 6.94 | 7.53 | 6.93 |
| 70 | 7.82 | 8.23 | 7.59 |
| 80 | 9.53 | 10.42 | 10.11 |
| 90 | 11.62 | 11.90 | 11.22 |
| 100 | 12.95 | 14.44 | 13.78 |
| 110 | 14.76 | 17.43 | 15.78 |
| 120 | 16.70 | 19.75 | 17.51 |
| | 3/8 ID Single Perforation Geometry | | |
| | (Density = 1.59 g/cc) | | |
| 30 | 1.37 | 2.26 | 2.49 |
| 40 | 2.70 | 2.61 | 2.92 |
| 50 | 4.49 | 4.62 | 5.21 |
| 60 | 6.53 | 6.41 | 6.57 |
| 70 | 7.55 | 7.33 | 8.17 |
| 80 | 10.20 | 8.81 | 10.29 |
| 90 | 11.91 | 10.65 | 12.39 |
| 100 | 14.05 | 12.93 | 14.57 |
| 110 | 16.63 | 15.34 | 17.29 |
| 120 | 18.63 | 17.12 | 19.35 |

Table 3. Effect of an increased surface area to volume ratio, cast TNT

| Pressure (MPa) | Quickness (MPa/ms) | |
|---|---|---|
| | #1 | #2 |
| | **Crushed TNT** | |
| 30 | 9.96 | 10.69 |
| 40 | 12.09 | 13.16 |
| 50 | 13.99 | 15.96 |
| 60 | 16.81 | 19.21 |
| 70 | 19.89 | 22.42 |
| 80 | 22.77 | 24.99 |
| 90 | 25.30 | 27.11 |
| 100 | 27.52 | 28.89 |
| 110 | 29.35 | 30.18 |
| 120 | 30.62 | 31.05 |
| | **Flake TNT** | |
| 30 | 13.33 | 14.97 |
| 40 | 16.70 | 17.12 |
| 50 | 20.61 | 19.72 |
| 60 | 24.30 | 22.57 |
| 70 | 27.25 | 25.39 |
| 80 | 29.78 | 28.06 |
| 90 | 31.79 | 30.57 |
| 100 | 33.68 | 32.91 |
| 110 | 35.28 | 34.95 |
| 120 | 36.63 | 36.68 |

Table 4. Test for interaction of wax with TNT

| Pressure (MPa) | Quickness (MPa/ms) | | |
|---|---|---|---|
| | #1 | #2 | #3 |
| | Solid Cylinder Geometry | | |
| | (Cast with 2.5% wax) | | |
| 30 | 4.28 | 4.87 | 4.80 |
| 40 | 6.53 | 8.02 | 8.24 |
| 50 | 9.36 | 11.54 | 11.49 |
| 60 | 11.34 | 13.07 | 14.34 |
| 70 | 15.41 | 14.20 | 15.27 |
| 80 | 19.19 | 17.24 | 17.38 |
| 90 | 21.71 | 20.59 | 20.46 |
| 100 | 23.53 | 23.30 | 23.43 |
| 110 | 25.05 | 25.42 | 25.63 |
| 120 | 26.29 | 26.86 | 26.90 |
| | 3/8 ID Single Perforation Geometry | | |
| | (Cast with 2.5% wax) | | |
| 30 | 2.73 | 2.41 | 1.74 |
| 40 | 7.75 | 5.98 | 4.12 |
| 50 | 12.17 | 9.42 | 8.24 |
| 60 | 15.57 | 12.16 | 13.26 |
| 70 | 17.21 | 13.74 | 16.22 |
| 80 | 17.84 | 15.86 | 18.59 |
| 90 | 19.66 | 19.44 | 20.76 |
| 100 | 22.16 | 33.01 | 22.82 |
| 110 | 24.33 | 35.10 | 24.65 |
| 120 | 25.61 | 25.88 | 26.08 |

Table 5. Test for the deconsolidation of the physical structure of cast TNT

| Pressure (MPa) | Quickness (MPa/ms) | |
|---|---|---|
| | #1 | #2 |
| | **Diameter Cup, 1.500 inch** | |
| 10.0 | 35.5 | 37.6 |
| 12.5 | 61.9 | 66.5 |
| 15.0 | 109.3 | 107.3 |
| 7.5 | 176.7 | 159.0 |
| 20.0 | 231.9 | 211.5 |
| 22.5 | 274.4 | 260.2 |
| 25.0 | 316.8 | 311.1 |
| 27.5 | 353.8 | 354.9 |
| 30.0 | 381.6 | 392.4 |
| 32.5 | 405.4 | 418.0 |
| 35.0 | 408.9 | 426.0 |
| 37.5 | 382.2 | 419.2 |
| 40.0 | 335.9 | 388.6 |
| | **Diameter Cup, 0.750 inch** | |
| 10.0 | 103.6 | 104.5 |
| 12.5 | 162.0 | 243.6 |
| 15.0 | 210.0 | 283.6 |
| 17.5 | 276.1 | 320.3 |
| 20.0 | 423.0 | 348.3 |
| 22.5 | 443.5 | 397.8 |
| 25.0 | 477.4 | 448.8 |
| 27.5 | 529.3 | 390.6 |
| 30.0 | 598.3 | 530.9 |
| 32.5 | 629.1 | 556.2 |
| 35.0 | 611.5 | 558.6 |
| 37.5 | 556.8 | 516.1 |
| 40.0 | 444.2 | 414.0 |

Table 6. Effect of crystal structure on burning of TNT

| Pressure (MPa) | Quickness (MPa/ms) | |
|---|---|---|
| | #1 | #2 |
| | Short Crystal Structure | |
| 10.0 | 29.5 | 26.2 |
| 12.5 | 45.9 | 34.2 |
| 15.0 | 79.2 | 54.2 |
| 17.5 | 113.0 | 84.1 |
| 20.0 | 159.5 | 113.7 |
| 22.5 | 198.8 | 148.7 |
| 25.0 | 246.3 | 178.9 |
| 27.5 | 291.8 | 205.6 |
| 30.0 | 324.9 | 236.5 |
| 32.5 | 349.9 | 261.5 |
| 35.0 | 369.3 | 281.4 |
| 37.5 | 359.9 | 290.4 |
| 40.0 | 344.1 | 277.7 |
| | Long Crystal Structure | |
| 10.0 | 123.1 | 67.7 |
| 12.5 | 220.5 | 138.5 |
| 15.0 | 292.6 | 241.2 |
| 17.5 | 385.0 | 327.8 |
| 20.0 | 432.8 | 394.0 |
| 22.5 | 506.8 | 471.6 |
| 25.0 | 574.8 | 553.7 |
| 27.5 | 637.8 | 645.7 |
| 30.0 | 684.9 | 714.1 |
| 32.5 | 740.7 | 769.0 |
| 35.0 | 745.0 | 825.3 |
| 37.5 | 732.5 | 849.5 |
| 40.0 | 662.6 | 839.0 |

Table 7. Effect of density on burning of pressed TNT

| Pressure MPa | Quickness MPa/s | | | | |
|---|---|---|---|---|---|
| | 1.510 (g/cc) | 1.525 (g/cc) | 1.559 (g/cc) | 1.604 (g/cc) | 1.664 (g/cc) |
| 10.0 | 204.4 | 95.1 | 18.7 | 32.5 | 25.7 |
| 12.5 | 391.5 | 196.7 | 52.5 | 55.0 | 32.6 |
| 15.0 | 542.5 | 327.6 | 84.6 | 103.8 | 38.8 |
| 17.5 | 546.3 | 461.3 | 163.9 | 152.7 | 51.2 |
| 20.0 | 772.4 | 520.6 | 265.9 | 197.9 | 62.3 |
| 22.5 | 863.7 | 571.1 | 349.2 | 244.2 | 76.3 |
| 25.0 | 960.6 | 641.5 | 420.2 | 309.6 | 91.4 |
| 27.5 | 1041.1 | 712.8 | 495.8 | 360.7 | 104.2 |
| 30.0 | 1113.7 | 781.0 | 571.3 | 400.3 | 120.3 |
| 32.5 | 1157.1 | 828.5 | 645.3 | 426.6 | 132.8 |
| 35.0 | 1177.7 | 860.8 | 688.4 | 446.6 | 136.8 |

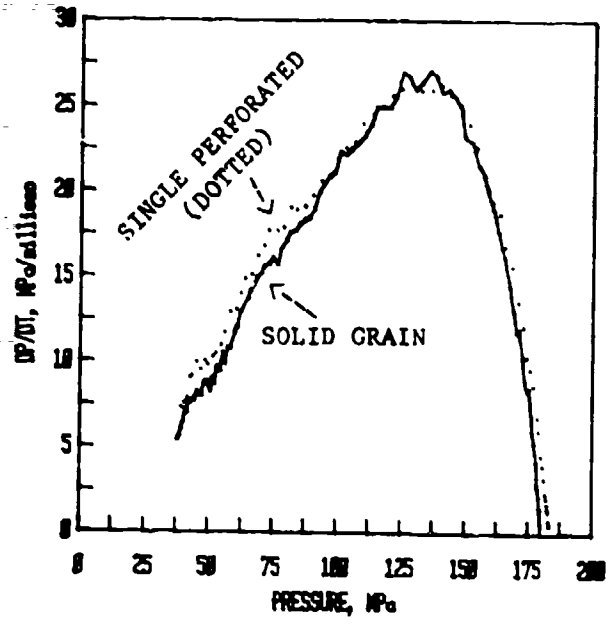


Figure 1. Cast TNT, test for surface burning (1.56 g/cm$^3$)

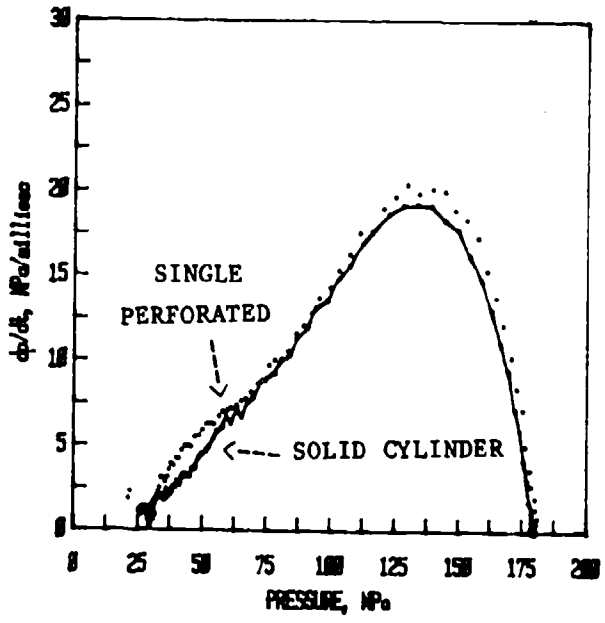


Figure 2. Pressed TNT, test for surface burning (1.59 g/cm$^3$)

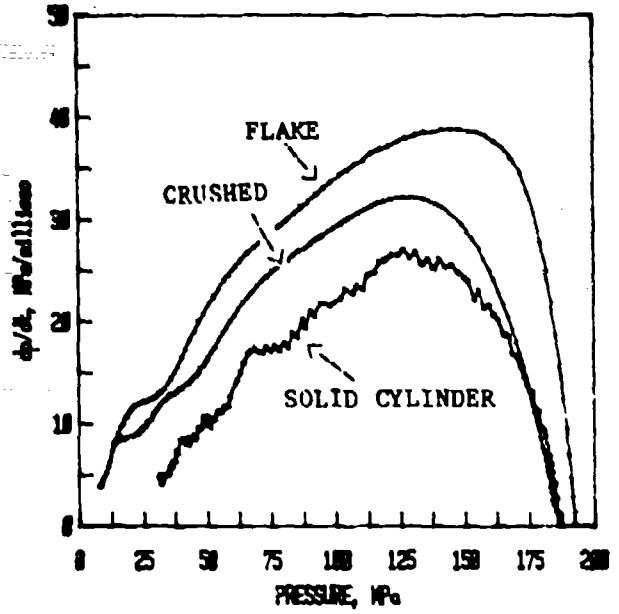


Figure 3. Crushed, flake, and solid TNT

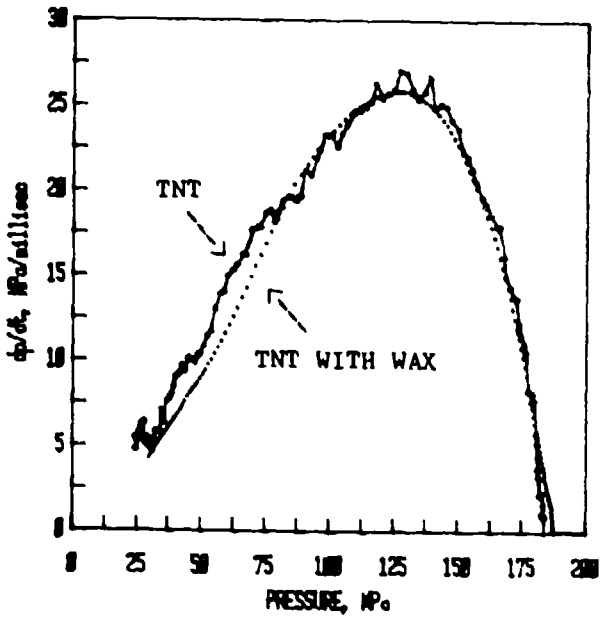


Figure 4. TNT, with and without wax

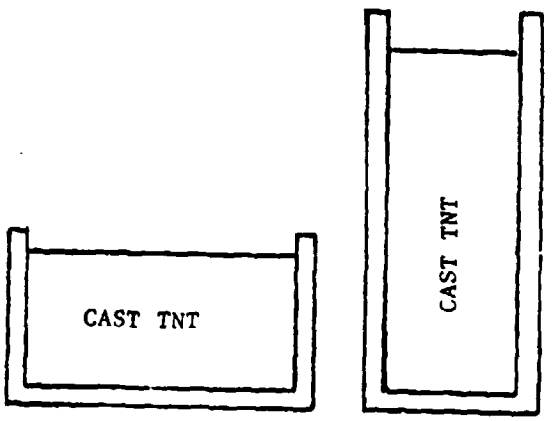


Figure 5. Restricted surface area cups

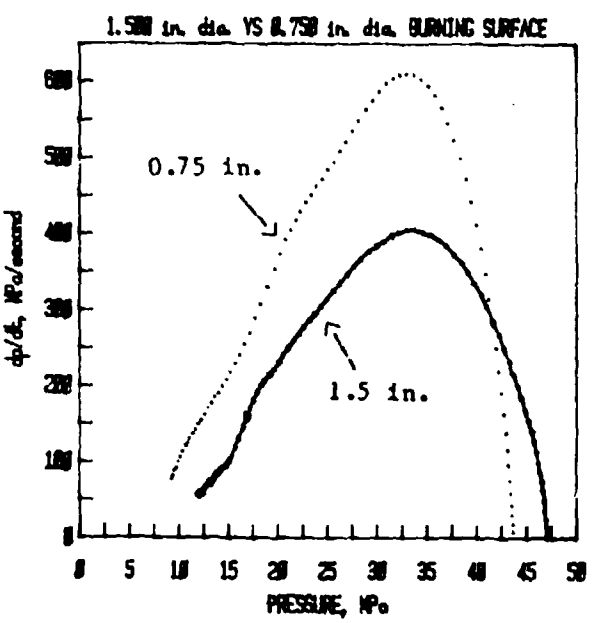


Figure 6. Fragmentation burning test

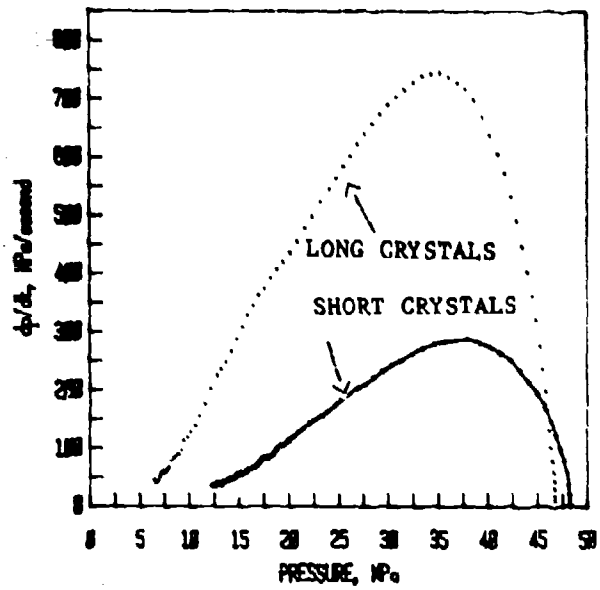


Figure 7. Crystal structure burning test

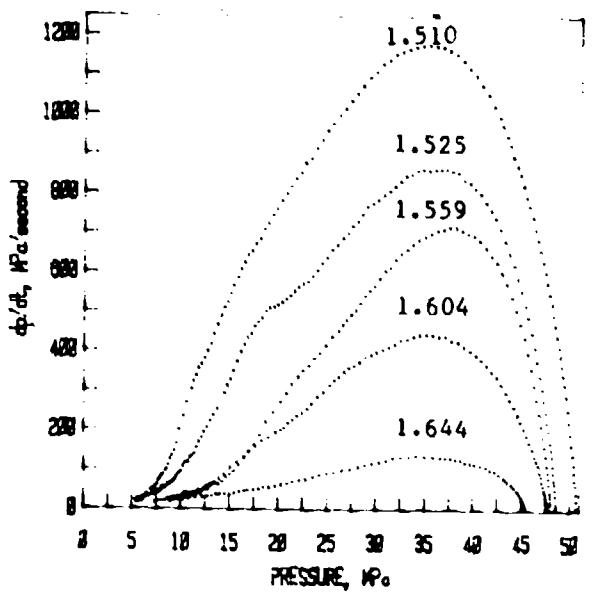


Figure 8. Density effect, pressed TNT

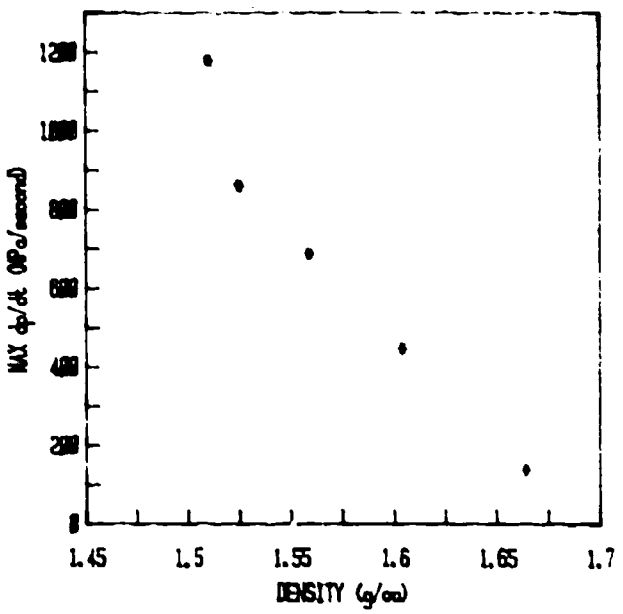


Figure 9. Density versus quickness correlation

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